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RADIATION CHARACTERISTICS OF MOIST GROUND IN THE UHF RANGE

A. Ye. Popov, Ye. A. Sharkov, and V. S. Etkin

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16. Abstract

Detailed calculations are made of the emissivity and the coefficient of polarization of radio emission of moist ground in the wavelength range from 0.8 to 226 cm and with moisture content up to 30 percent. The calculations are based on experimental moisture functions of electrical parameters of the ground. The limits to the applicability of the approximation tg $\delta \ll 1$ are indicated. The effect of atmospheric glow on the radiobrightness temperature and the coefficient of polarization of the radio emission of moist ground is examined. It is shown that the wavelength range of 20-75 cm is optimal for the measurement of the moisture content. A brief review is given of experimental data in the literature.

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AUTHORS' ABSTRACT /2

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INTRODUCTION /3

One of the interesting and promising problems in remote passive probing in the UHF range is the determination of the moisture of earth cover and subsurface structures [1, 2, 3, 4, 5, 6].

The present study gives detailed calculations of the radiation characteristics as well as of radiobrightness temperatures[1] of sandy and clay ground (of definite chemical composition and density) as a function of moisture content of soil in a wide wavelength range.

Similar calculations in [2] do not make allowance for several essential factors that affect the emission of a medium, such as the quenching in moist ground, atmospheric glow, and nonlinearity of the dependences of the dielectric permittivity and coefficient of of absorption on moisture. Therefore the calculations in [2] must be regarded as valid only to the first approximation. The calculations described below are based on experimental dependences of the electrical characteristics of ground on moisture [7].

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[1] With allowance for atmospheric glow.

RADIATION CHARACTERISTICS OF MOIST GROUND IN THE UHF RANGE /4

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1. Electrical Characteristics of Moist Ground

In [7], sandy and clay ground at temperatures of 18-20°C and moisture content up to 30 percent was investigated in the wavelength range 0.8-226 cm. The sandy soil had a physical clay content less than several percentages, a density 1.85 g/cm^3, and a total of absorbed (exchange) bases of calcium and magnesium equal to 1.0-1.5 milligram-equivalents per 100 g absolutely dry soil. The clay soil had a sand content less than 20 percent, density 1.67 g/cm^3, and total absorbed bases of calcium and magnesium equal to 24.8-25.8 milligram-equivalents per 100 g absolutely dry soil.

Fig. 1 presents in its upper section the wavelength functions of the dielectric permittivity, plotted directly from the data in [7], and in its lower part -- the wavelength functions of tg δ calculated from experimental values of attenuation in soil [7] (the solid line stands for sand, the dashed line stands for clay). These functions show that in the range of wavelengths shorter than 5-8 cm, for moisture exceeding 3-4 percent, sand cannot be considered as material with low losses and cannot be used in calculation by appropriate simplifications. At the same time, the approximation indicated (tg $\delta \ll 1$) is valid for sand in the 10-200 cm range for all moisture contents up to 20-25 percent. As for clay soil, losses in it cannot be assumed in the 8 mm/- 300 cm wavelength range (that is, virtually over the entire UHF range). These features must be taken into account in calculations of the radiation characteristics of ground.

It should be noted that the dependence of attenuation on moisture approximated in [2] by a linear function actually is more complicated. For low moisture, there is a discontinuity in this function in the value of the attenuation associated with change in /5 the carrier of attenuation in moist ground, initially this is film moisture, and then free water [8, 9]. In complex soils containing organic additives, humidification will appear more complex by virtue of the chemical interaction of free water with the forming soil skeleton, analogous to the humidification of clay where most of the attenuation (in meter range) is due to admixtures dissolved in the water (Fig. 1).

2. Emissivity and Radiobrightness Temperature of Moist Ground

The radiobrightness temperature T_{br} of radiation from a semiinfinite medium with a smooth surface and an arbitrary distribution depthwise of dielectric permittivity $\dot{\varepsilon}(z) = \varepsilon_0 (1 - j\,\mathrm{tg}\,\delta)$ and physical temperature $T(z)$ (z = depth) is determined by the equality [1, 10]:

$$T_{br} = \varkappa T_{ef} + |\dot{R}|^2 T_H, \qquad (1)$$

$$\varkappa = 1 - |\dot{R}|^2, \qquad (2)$$

where $\varkappa$ is the emissivity of the medium, $\dot{R}$ is the complex coefficient of reflection, $T_{ef} = \int T(z)\gamma(z)\exp\left[-\int \gamma(z')\,dz'\right]dz$ (3)

is the effective temperature of the radiating layer, $\gamma(z)$ is the coefficient of absorption of the medium, and T_H is the brightness temperature of the atmosphere. The value of T_{ef} determines the energy flux formed in the medium, and $\varkappa$ characterizes the fraction of this energy escaping through the interface.

In [11] it is shown that the soil inhomogeneities actually encountered in natural conditions depthwise weakly affect emissivity, and the effect of inhomogeneity becomes substantial only for dry /6 ground at wavelengths longer than 60 cm, therefore we consider only depthwise homogeneous soil.

The isothermal (depthwise) medium is the simplest, and an important specific case of Eq. (3): $T(z) = T_0$. The distribution with respect to the surface coordinates $T(x, y)$ can in principle be arbitrary. And it is not difficult to show that the main contribution ($\sim$ 90 percent) to the radio emission of a semi-infinite medium is made by a finite effective layer, whose thickness in the case $\gamma(z) = \gamma_0 = \text{const}$ is:

$$\ell_{ef} \lesssim 2.3/\gamma_0, \tag{4}$$

$$\gamma_0 = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_1}{2}\left(\sqrt{1+tg^2\delta}-1\right)}, \qquad \text{neper}\cdot\text{m}^{-1}\ [2]$$

where λ is the wavelength of air, and δ is the angle of electrical losses in the radiating medium. The calculated values of the quantity ℓ_{ef}/γ at 10 percent moisture is 4.5 (1) for sand (clay) in the 20 cm range, and in the 75 cm range -- 5.3 (0.53).

Since we are considering an isothermal medium with a smooth surface, its emissivity $\varkappa$ is entirely determined by the complex dielectric permittivity $\dot{\epsilon}$ and for observations at the nadir, we have

$$\varkappa = \frac{4\sqrt{\varepsilon_1 \cos\delta}\,\cos\frac{\delta}{2}}{\varepsilon_1 + \cos\delta + 2\sqrt{\varepsilon_1\cos\delta}\,\cos\frac{\delta}{2}}. \tag{5}$$

Fig. 2 gives the dependences - calculated based on Eq. (5) -- of the emissivities of clay (a) and of sand (b) on moisture for several wavelengths. The contribution to the emissivity of a medium from the imaginary part of $\dot{\epsilon}$ represents a relative value up to 30 percent for a moisture of about 20 percent, and therefore this contribution cannot be neglected[3]. /7

[2] Usually in experimental studies, γ is given in db/m; $\gamma(\text{db/m}) = 8.7\ \gamma\ (\text{neper/m})$.

[3] /on following page/

From an analysis of the plots in Fig. 2, it is clear that for small ($m < 5$ percent) and large ($m > 1$ percent) moisture values, the dependence of $\chi(m)$ deviates appreciably from the linear. We can speak about the linearity of these functions (and also in the case of the isothermal model, about the radiobrightness temperature) only in a restricted range of moisture values, approximately from 5 to 15 percent, where its interval depends on the working wavelength range and on the type of ground. When there are large variations in moisture, we must use the graphs in Fig. 2 as calibration curves. From the practical standpoint, it is important to know the variation in χ (or in the radiobrightness temperature) per percent of moisture change.

Estimates of change in radiobrightness temperature per percent of moisture without taking atmospheric glow into account in the linear section of the plot for $T_0 = 300^{\circ}K$ yield, for clay soil at the wavelength 226 cm -- 8.3 degrees per percent, for 90 cm -- 7.2, for 10 cm -- 6.3, for 3 cm -- 5.7, and for 0.8 cm -- 5.1.

For sandy ground, this value is practically constant over the entire range of wavelengths considered and is about $6^{\circ}K$. For moisture higher than 15 percent, at all wavelengths a sharply nonlinear section of saturation commences, where principally the main contribution to radio emission is given by the aqueous solution.

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[3] In the calculations given in [2] of the analogous functions, first of all the effect on χ of the imaginary part of the dielectric permittivity was not taken into account; secondly, ϵ_1 was assumed to be proportional to moisture at all moisture values. Accordingly, the plots given in [2] must be considered as approximate, especially for small ($m < 5$ percent) and large ($m > 15$ percent) moisture values.

Fig. 3 gives the moisture dependence of radiobrightness temperature /8 with allowance for atmospheric glow, calculated by Eq. (1) for T_{ef} = 300°K (the solid line corresponds to sand, and dashed -- to clay). The noise temperature of the atmosphere T_H at the zenith /12/ does not exceed 10°K in the 3-30 cm range, while for further increase in the wavelength it rises sharply to 500°K at λ = 300 cm [4]. The presence of atmospheric glow makes the functions T_{br} (m) (Fig. 3) more gradual than without allowance for glow, and this effect, not very appreciable for wavelengths from 3 to 30 cm, for λ = 226 cm leads to the virtually complete independence of the radiobrightness temperature of the ground (both sand as well as clay) of moisture. The variation in the brightness temperature, for a 1 percent change in moisture, in this case at wavelength 90 cm is 6.7 (4.2) degrees per percent for sand (clay), 7.1 (6.2) -- at a wavelength of 30 cm, and 6.5 (6.0) -- at 3 cm.

These estimates show that the maximum value is attained by $\Delta T_{br}/\Delta m$ in the decimeter range (at wavelength of the order of 10-20 cm).

3. Polarization Characteristics of Moist Ground

Complete expressions for the vertical (χ_v) and horizontal (χ_h) components of emissivity for an arbitrary angle of observation θ (the measurement of θ is made from the vertical) and for a homogeneous semiinfinite medium with arbitrary losses can be written as:

$$\chi_V = \frac{4\beta|\dot{\varepsilon}|\cos\theta\cos(\delta-\frac{\varphi}{2})}{\beta^2+|\dot{\varepsilon}|^2\cos^2\theta+2\beta|\dot{\varepsilon}|\cos\theta\cos(\delta-\frac{\varphi}{2})} \qquad (7)$$

[4] With increase in the angle of observation θ (as one approaches the horizon), the noise temperature of the atmosphere rises: $T_k = T_z/\cos\theta$, where T_z is the temperature at the zenith ($\theta = 0°$). This formula is sufficiently exact up to angles $\theta \leqslant 85°$ /12/.

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$$\mathfrak{X}_h = \frac{4\beta\cos\theta\cos\frac{\varphi}{2}}{\beta^2 + \cos^2\theta + 2\beta\cos\theta\cos\frac{\varphi}{2}}, \tag{8}$$

$$\beta = \sqrt[4]{(\varepsilon_1 - \sin^2\theta)^2 + \varepsilon_1^2 \operatorname{tg}^2\delta},$$

$$|\dot{\varepsilon}| = \varepsilon_1\sqrt{1 + \operatorname{tg}^2\delta}, \quad \varphi = \operatorname{arctg}\frac{\varepsilon_1 \operatorname{tg}\delta}{\varepsilon_1 - \sin^2\theta}$$

The coefficient of polarization P is defined by the relation /1/:

$$P = (T_{br,v} - T_{br,h})/(T_{br,v} + T_{br,h}). \tag{9}$$

The effect of temperature for any angle of observation is /10/:

$$T_{ef} = \int_0^\infty T(z)\gamma(z)\sec\theta' \exp\left[-\int_0^z \gamma(z')\sec\theta' dz'\right] dz, \tag{10}$$

where θ' is the angle of incidence of the radiation at the interface of the media: it is associated with the angle of observation θ in the first medium (vacuum or air) by the law of refraction ($\operatorname{tg}\delta \ll 1$ is assumed for the radiating medium) /10/:

$$\cos\theta' = \sqrt{1 - \frac{\sin^2\theta}{\varepsilon_1}} \tag{11}$$

Since T_{ef} in (10) does not depend on the kind of polarization, (9) becomes simplified:

$$P = (\mathfrak{X}_v - \mathfrak{X}_h)/(\mathfrak{X}_v + \mathfrak{X}_h). \tag{12}$$

Hence follows an important conclusion: the coefficient of polarization does not depend on the depth profile of the thermodynamic temperature of the semiinfinite layer.

Calculations based on Eqs. (7), (8), and (12) show that the dependence of the polarization coefficient on moisture (Fig. 4) is linear, with a slope of about 1 percent per 1 percent of moisture for clay, and 0.6-1.0 percent per 1 percent moisture for sand up to moisture values of 15-20 percent, after which the tendency to saturation again begins to be manifested. If the /10 radiometric system permits distinguishing the variation per 1 percent of the coefficient of polarization (here we have in mind not the relative percentages, but the percent as a unit of measurement of the coefficient of polarization), then when $\theta = 45^{\circ}$, we can with confidence distinguish the order of ten gradations of moisture from 0 to 20 percent.

Let us estimate the effect of the atmospheric glow on the polarization measurements. Substituting in (9) Eq. (1) with subscripts at $\varkappa$ and $\dot{R}$, corresponding to the vertical in horizontally polarized components of radiation, and referring to (2), we get

$$P = \frac{\varkappa_v - \varkappa_h}{\varkappa_v + \varkappa_h + \frac{2T_h}{T_{ef} - T_h}} . \qquad (13)$$

In Fig. 5, the solid line represents the dependences of the coefficient of polarization P, calculated by Eq. (13), on the angle of observation and on the wavelength for clay with a 10 percent moisture ($T_{ef} = 300^{\circ}K$).

The dashed line denotes these same functions without allowing for atmospheric glow (Eq. (12)).

As we can see in Fig. 5a, the difference between the values of the coefficient of polarization with allowance for glow and the same values without allowance for glow reaches maximum (more than 30 percent when $\lambda = 0.8$ cm, $\theta = 80^{\circ}C$). At large angles of observation ($\theta > 80^{\circ}$), a maximum appears in the function $P(\theta)$, and then a decline [5].

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[5] A similar effect was encountered in an examination of the polarization characteristics in the centimeter range (near the line of absorption of water), with allowance for the increase in the atmospheric temperature with rise in the angle of observation /13, 14/.

For each angle of observation (see Fig. 5b), there is some critical wavelength λ_{cr} at which the coefficient of polarization tends to zero, which corresponds to the case $T_H = T_{ef}$. This wavelength λ_{cr} mainly lies in the range 1.5-2.5 m and increases with decrease in the angle of observation. /11

4. Several Methodological Comments

From Fig. 2 and the estimates of $\Delta T_{br}/\Delta m$ without allowance for atmospheric glow, we can see that emissivity in the long-wave section of this range is most sensitive to change in moisture, and with increase in the wavelength the effective depth of radiation also rises, that is, the depth of probing.

However, the abrupt rise at long wavelength in the effect of atmospheric glow limits the optimal wavelength range to about 50-80 cm. In addition, use of the meter waves is restricted by the possibilities of housing large antenna systems on an airplane or a spacecraft /3/, therefore evidently we must consider the decimeter range of UHF to be optimal.

To determine the total moisture content in a specific type of ground, we can propose the following procedure: after cartographic tie-in of radiobrightness temperature data and infrared sensor data, the emissivity of the element of resolution is determined, and then its moisture (with allowance for the ground type). Knowing the working range of wavelength and the moisture, let us determine the effective depth of radiation (see Eq. (4)) and the volume of the element of resolution $V = S\ell_{ef}$ (S is the area of the averaging spot on the surface being examined). If we know the structure of dry ground (for example, the specific weight of the soil skeleton g_{sk} or the specific weight g_0 and porosity n), we can estimate the total moisture content q_m[6] of the volume of the element of resolution, using the relation /12

/Footnote 6 on following page/

$$q_m = S\ell_{ef}g_{sk}(0.01\ m) = S\ell_{ef}g_0(1 - n)(0.01\ m).$$

Thus, when soil maps (soil cadastres) of the region under study are available, effective determination of the moisture and monitoring of its variation are possible. This possibility can be highly useful determining the schedules of agricultural work, when areas in need of irrigation appear, and in other requirements.

When IR radiation is absorbed by clouds, for onboard measurements it is necessary to develop methods of determining temperature and moisture by simultaneous measurements at several wavelengths in the UHF range.

5. Review of Experimental Data

Experiments whose results were published in [11] are the closest (in the sense of the laboratory method of their execution). This study gives the following experimental values for the emissivity of dry river sand of medium granularity, with an even surface: at the wavelength 1.6 cm -- 0.933, and at 0.8 cm -- 0.939. At the wavelength 3.2 cm, the emissivity of moist sand is as follows: for 3.4 percent of moisture -- 0.927, for 10 percent moisture -- 0.703, and for 14.5 percent moisture -- 0.655. The corresponding values were calculated are 0.93 for dry sand in both wavelengths; 0.88, 0.75, and 0.67 for wet sand.

From the data of onboard experiments [15], at the wavelength 0.95 cm the change in T_{br} per percent change in moisture is 5-6°K, which agrees well with our calculations (See Section 2). /13

[6] In deriving this relation, we used the definition of porosity $n = (d_0 - d_{sk})/(d_{sk})$; the specific weight of the soil skeleton is equal to the ratio of the weight of the mineral portion (skeleton) of the rock to the total volume (including the volume of the pores [8]).

Typical experimental values of the sensitivity of the radiobrightness temperature to change in moisture, given in a brief review [3] are 3-5°K per percent in the 0.8-20 cm range for a total drop in T_{br} of 100°K, with variation in moisture from 5 to 25 percent.

In the state of Arizona a cartographic survey was made of agricultural lands by using a scanning radiometer at the wavelength 1.55 cm (19.35 GHz) mounted on an aircraft (flight altitude 1 km) [16]. The process information was represented in the form of a colored map, where each of the five colors denotes a different degree of wetness. The dry section (6 percent moisture) had a radiobrightness temperature of 275°K, and the wettest (35 percent) -- 220°K.

Thus, to each color gradation there corresponded an approximately 10°K drop in the radiobrightness temperature and about a 6 percent drop in the moisture. According to the onboard IR observations, the thermodynamic temperature of the Earth's surface was 291 ± 4°K, the indeterminacy in the measurement of the radiobrightness temperature was 5-6°K.

The results of the quantitative measurements in the study are approximated by the linear dependence of the radiobrightness temperature on moisture, which is acceptable only for moisture values from 5 to 15 percent. This can account for such a low value of the quantity $\Delta T_{br}/\Delta m \approx 1.7$.

The electrical characteristics of soil in this study are not indicated, therefore any direct comparison with our calculations is difficult. We can only note that the trend toward a decrease in the slope of the linear part of the curve $\varkappa(m)$ with increase in the working frequency is clearly observed also in our calculations, however the size of this coefficient is three to four times higher than in the study cited. /14

Polarization experiments aimed at a quantitative analysis of the moisture functions of the emissivity of different polarizations and of the polarization coefficient are few in the literature. We can point to the experimental dependences of horizontally and vertically polarized components on the angle of observation for three degrees of moisture (12 percent, 21 percent, and 30 percent) obtained with a radiometer in the 13.5 GHz range in arid regions of the United States [5, 6]. These curves correlate quite well with our calculated functions, but since the experimental details have not been presented, it is difficult to make a quantitative comparison.

The first methodological satellite experiment showing the possibility of using multifrequency radiometric methods for problems of determining the degree of moisture in earth cover was conducted on the Kosmos 243 AES [artificial earth satellite]. Even in the first publications (for example, [17]), profiles of the radiobrightness temperatures are given for several regions of the globe, which permit a clear distinguishing of large areas with wetness (swamped river deltas, oases, and dried-out rivers in deserts), and also to roughly estimate the degree of wetness from the depression of the radiobrightness temperature. A closer combined study of ground (moisture monitoring) and onboard (analysis of the field of UHF radio emission) data led the authors of [18] to the following interesting results. With a large space-time averaging (a spot on the earth's surface was about 2000 km^2), the emissivity of the cultivated landscape of the European part /15 of the USSR (September 1968) in the 0.8 cm range in general was independent of moisture, and the radiobrightness temperature corresponded to the thermodynamic temperature with a correlation coefficient of 0.92.

This indicates that with large averaging for the 0.8 cm range and shorter, the cultivated landscape is a diffuse (Lambertian) surface. At longer wavelengths (3.4 and 8.5 cm), analysis of the experimental data in [18] was carried out by constructing over a wide interval of moisture values (from 10 to 40-45 percent) a linear regression, which has a slope in these ranges of about 0.7-0.8°K per percent of moisture change.

Conclusions

1. The contribution to the emissivities due to attenuation in moist sand in the wavelength range shorter than 0.8 cm and in moist clay in the wavelength range 0.8-300 cm is very appreciable, and the approximation tg $\delta \ll 1$ cannot be used in calculations.

2. The dependence of emissivity and the coefficient of polarization of moist ground on moisture can be assumed linear in the range of moisture values 5-15 percent. Outside this interval, the functions are nonlinear.

3. Atmospheric glow fundamentally limits the range of wavelength applicable for remote methods to wavelengths of the order of 1 meter.

The presence of atmospheric glow reduces both the sensitivity of the radiobrightness temperature to moisture change (especially at wavelengths above 80 cm), as well as the angular dependence of the coefficient of polarization and leads to the appearance of maximum and this function at the angles of incidence 70-85°. /16

4. We can regard the decimeter range (20-75 cm, depending on the required probing depth) as optimal for passive remote probing of moist structures.

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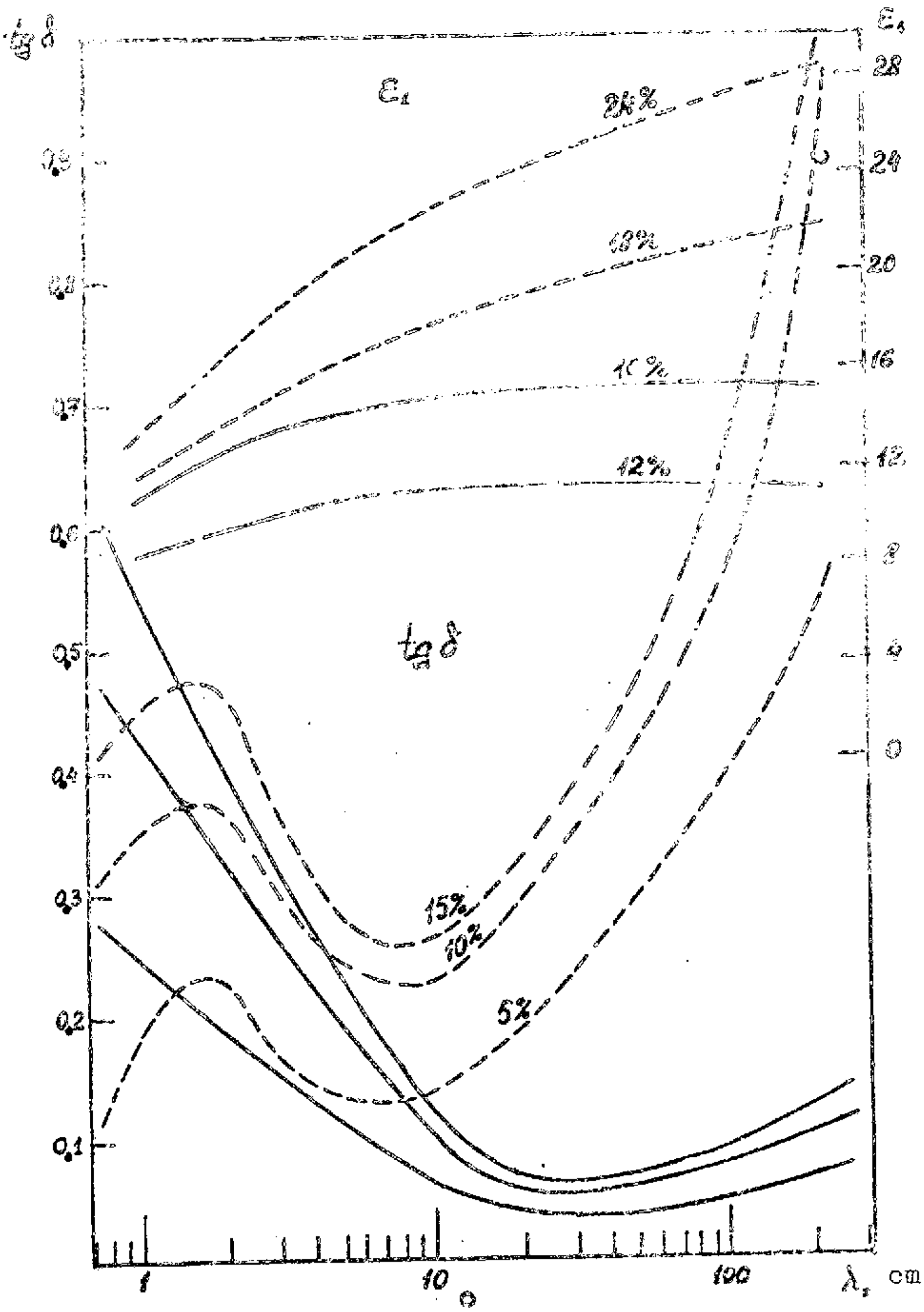

Fig. 1. Dependence of real part of dielectric permittivity and loss tangent on wavelength for different soil moisture content; solid line -- sand; dashed line -- clay

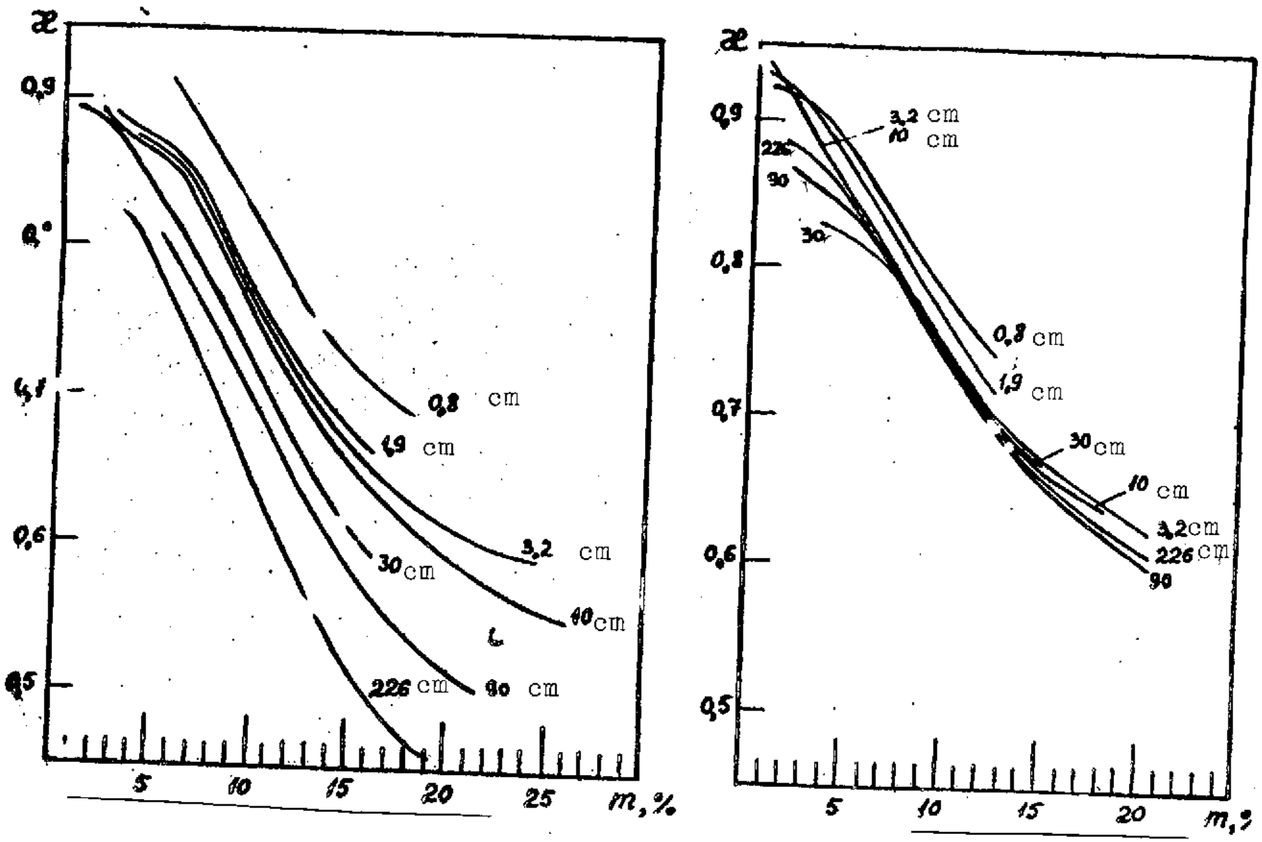

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Fig. 2. Dependence of emissivity of clay (a) and of sand (b) on moisture for various wavelengths

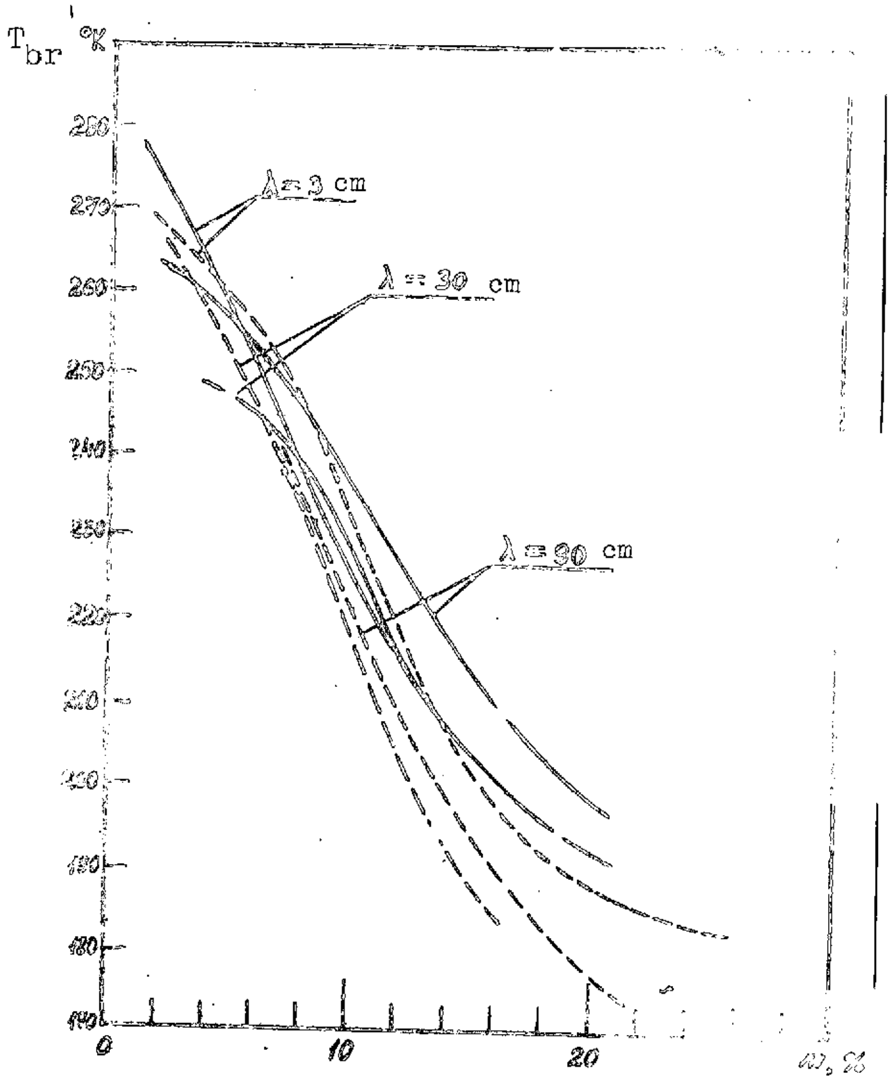

Fig. 3. Radiobrightness temperature of moist sand (solid line) and clay (dashed line) with allowance for atmospheric glow as a function of moisture for several wavelengths

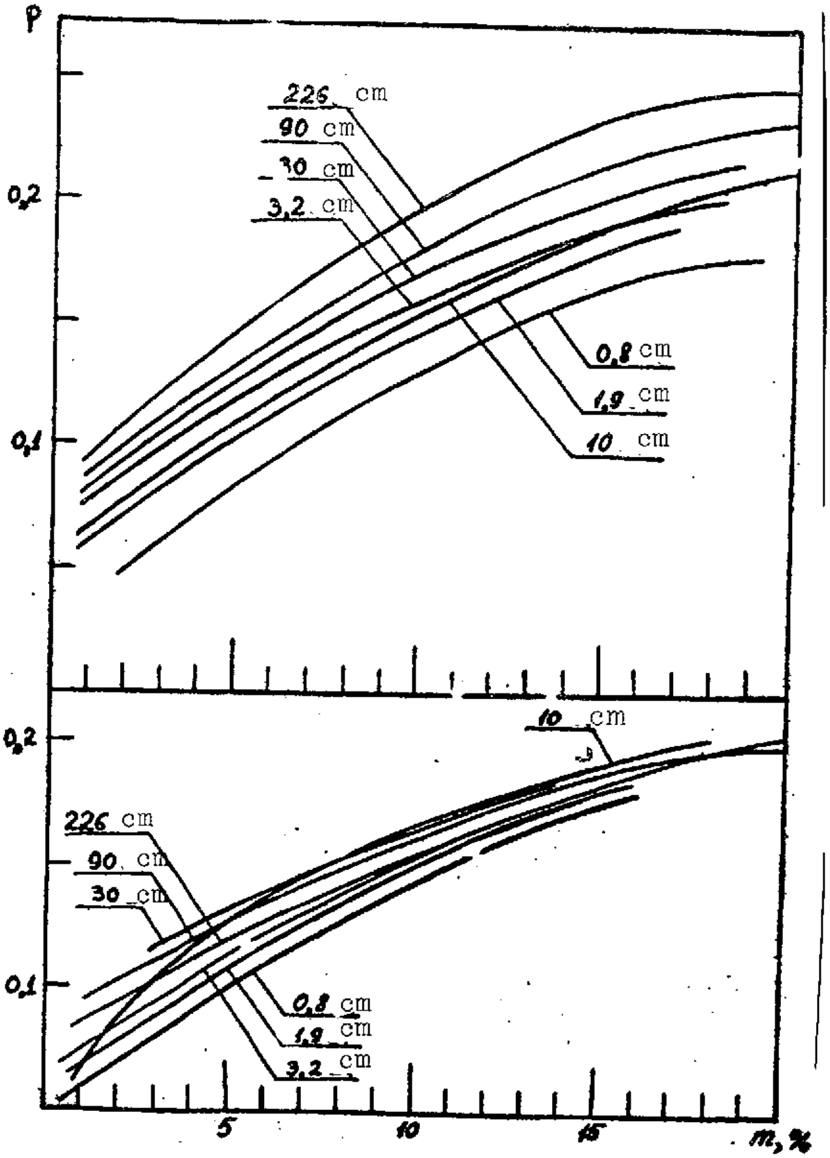

Fig. 4. Coefficient of polarization of the radio emission of clay (a) and of sand (b) without allowance for atmospheric glow, as a function of moisture for different wavelengths. Angle of observation $\theta = 45^{\circ}$

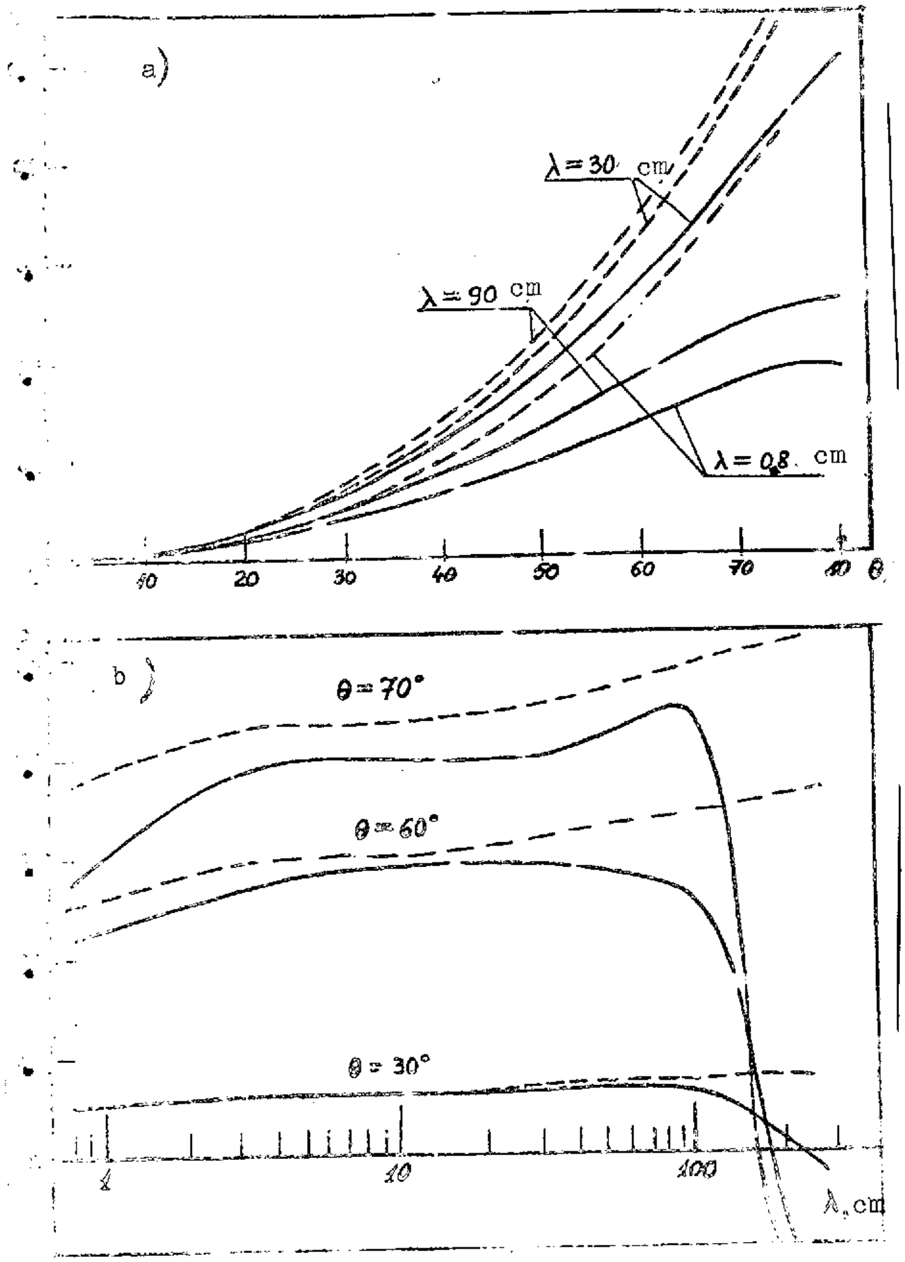

Fig. 5. Coefficient of polarization of the radio emission of clay with 10 percent moisture as a function of angle of observation (a) and wavelength (b), with allowance for atmospheric glow; $T_{ef} = 300^{\circ}$ K.